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High Density Constraint on the Entropy Instability

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Abstract

The entropy instability[2] is a nonisothermal effect which is eliminated by parallel ion pressure at high densities ($k_z \lambda_e < 1/2 \sqrt{m/M}$), reducing previous growth rate estimates and the range of unstable parameters.

The entropy mode[1] is basically a non-propagating, periodic electrostatic disturbance in a collisional plasma, with temperature fluctuations comparable to density fluctuations which are $\sim\pi$ out of phase[2]; it is therefore a constant pressure perturbation. It has also also been called a diffusion mode because in the absence of a density gradient,[1] nonlinear coupling to an electromagnetic pump wave in stimulated backscattering,[3] or some additional source of free energy, the entropy mode relaxes at the cross magnetic field diffusion rate. Tsai et al.,[1] have shown that the entropy mode is destabilized by a density gradient at high densities where collisions reduce electron heat conduction and nonisothermal effects are important. We will show that it is stabilized at high densities by parallel ion pressure and energy transfer between species which they have neglected, thereby reducing previous growth rate estimates and the range of unstable parameters.

Dispersion Relation

We assume that a strongly ionized slab plasma with an X-directed density gradient of scale length $L_\perp$ is immersed in a uniform, Z-directed magnetic field. The entropy instability then appears in the two fluid, electrostatic dispersion relation for low frequency ($\omega << \omega_{pi}$, Ω_i and $(\nu_{ei} + \nu_{en})$, long wavelength ($k_z \lambda_e < 1$) modes[4]:

$$\nu_\parallel \frac{\left[\omega + i\nu_\parallel(\bar{\chi} - \bar{\xi})\right]}{\left[\omega + i\nu_\parallel \bar{\chi}\right]} = \frac{i\left\{\left(\omega + R_T\omega_D\right)(b\omega + i\nu_\perp - k_z^2 C_s^2/\omega)\right\}}{\left\{\omega\left[1+\rho b\right] - \omega_D + i\nu_\perp\rho - \left(k_z^2 C_s^2/\omega\right)\rho\right\}} \qquad (1)$$

$b = k_y^2 C_s^2/\Omega_i^2$ is the ion finite Larmor radius (FLR) parameter and $\omega_D = k_y C_s^2/\Omega_i L_\perp$ is the diamagentic drift frequency in terms of the ion acoustic speed $C_s^2 = T_e/M$; $\nu_\perp/b = \nu_{in} + 0.3b\,\nu_{ii}$ scales the perpendicular

ion diffusion rate, $\nu_{\parallel} = k_z^2 a_e^2/(\nu_{ei} + \nu_{en})$ the parallel electron heat conduction rate; ν_{ii}, ν_{in}, ν_{ei} and ν_{en} are collision frequencies (i = ions, e = electrons and n = neutrals), assumed small compared to respective cyclotron frequencies Ω_i and Ω_e, and plasma frequencies ω_{pi} and ω_{pe}, and $R_T = T_i/T_e$ is the temperature ratio. $\overline{\chi}$ and $\overline{\xi}$ are combinations of finite electron heat conduction terms [5, 6] which are important for $\sqrt{m/M} \leq k_z\lambda_e < 1$, and energy transfer terms proportional to m/M which dominate at high densities and long parallel wavelengths ($k_z\lambda_e \leq \sqrt{m/M}$):

$$\overline{\chi} = 2/3\left[C_r C_x + \left(1 + C_t\right)^2\right] + i2(m/M)\,\nu_e/\nu_{\parallel} + i\,.\left(1 - R_T\right)(m/M)\left(\nu_{en} - 3\nu_{ei}\right)/\nu_{\parallel} \tag{2a}$$

$$\overline{\xi} = 2/3\left(1 + C_t\right)^2 + 2\left(1 + C_t\right)\left(1 - R_t\right) \cdot (m/M)\left(2\nu_{ei} + \nu_{en}\right)/\nu_{\parallel} \tag{2b}$$

Previous results[1] are recovered neglecting neutral collisions, parallel ion pressure which yields the acoustic coupling terms $(k_z^2 C_s^2/\omega)$, and energy transfer between species in $\overline{\chi}$ and $\overline{\xi}$. The entropy mode which is coupled to interchange, drift and acoustic terms on the right hand side of (1) is decoupled and damped in the limit $b \to 0$; like the drift mode [1, 4] the entropy instability is an ion FLR effect.

Finite Heat Conduction Limit

The entropy mode which is almost purely growing is decoupled from (1) assuming $\omega/\omega_D << 1$, $b << 1$ and $\nu_\perp/\nu_\parallel \sim 1$, yielding a growth rate

$$\gamma = \frac{\nu_\parallel(\bar{\chi} - \bar{\xi})\left\{\left[1 - \frac{\bar{\chi}}{\bar{\chi} - \bar{\xi}}\frac{\nu_\perp R_T}{\nu_\parallel} + \frac{k_z^2 c_s^2}{\nu_\parallel^2(\bar{\chi} - \bar{\xi})}\right]\left(\frac{\nu_\perp}{\nu_\parallel}R_T - 1\right)\left(\frac{\nu_\perp \rho}{\omega_D}\right)^2\right\}}{\left(1 - \frac{\nu_\perp R_T}{\nu_\parallel}\right)^2 + \left(\frac{\nu_\perp \rho}{\omega_D}\right)^2} \tag{3}$$

In the limit $\nu_\perp / \omega_D << 1$ required for instability this reduces to the result obtained by Tsai <u>et al.</u>[1], neglecting neutral collisions, parallel ion pressure, and energy transfer terms. For $\nu_\perp / \omega_D << 1$, the range of unstable $R_T \, \nu_\perp / \nu_\parallel$ is

$$\left[1 + (m/2M)\left(1/k_z^2\lambda_e^2\right)/(\bar{\chi} - \bar{\xi})\right](\bar{\chi} - \bar{\xi})/\bar{\chi} < \left(R_T \nu_\perp / \nu_\parallel\right) < 1 \tag{4}$$

This range vanishes for $k_z \lambda_e < \frac{1}{2}\sqrt{m/M}$ as a result of the acoustic correction terms in (1), previously neglected; hence the entropy mode is stabilized at high densities in general.

In Figure 1 we have plotted the maximum unstable density parameter $N = 0.3 L_\perp / \lambda_e$ vs. $\nu_\perp / \nu_\parallel$ for a fully ionized plasma, as determined by the acoustic constraint $k_z \lambda_e < \frac{1}{2}\sqrt{m/M}$. It is apparent that for high densities $N \geqslant 8.7$ the entropy mode is always stable; in particular, it is stable in the case where Tsai <u>et al.</u>[1] have computed a positive growth rate neglecting parallel ion pressure for $N = 9.08$. At lower N values the drift mode [1, 4] typically grows faster than the entropy mode whose growth rate and range of unstable $\nu_\perp / \nu_\parallel$ given by equations (3) and (4) are reduced by the acoustic correction.

The acoustic constraint which requires $k_z \lambda_e > \frac{1}{2}\sqrt{m/M}$, hence $N = 0.3 L_\perp / \lambda_e \leqslant 8.7$, determines a minimum parallel wavelength for instability in a fully ionized plasma, $\lambda_z \geqslant 75 \, L_\perp$. For typical Q-machine density gradient scale lengths ($L_\perp \sim 1$ cm), unstable parallel wavelengths

are the order of the machine length. In the nighttime equatorial F region ionosphere where the vertical density gradient scale length typically drops to $L_\perp \sim 20$ km, the minimum unstable parallel wavelength $\lambda_z \sim$ 1500 km. This exceeds the geometric cutoff [7] on parallel wavelength for modes localized to the region of sharpest density gradient, namely the distance over which the dipole field line drops in altitude by one scale length $L_\perp$ in a vertically stratified ionosphere: $\lambda_z^{max}/2 = \sqrt{L_\perp R_e}$ (R_e is the radius of the earth). Applying this criterion to the entropy mode requires extremely short scale lengths for instability: $L_\perp < 4.5$ km. Thus, while the entropy instability may be observable in the laboratory under conditions which favor the drift mode (low density), it is not likely to be a significant linear instability in the ionosphere. We now show that the entropy instability is further restricted in a partially ionized plasma by energy loss to the neutrals.

Isothermal Limit

The isothermal limit is formally recovered from (1) by letting $\overline{\chi} \rightarrow \infty$ for finite $\overline{\xi}$, which eliminates the entropy root; consequently the range of unstable $R_T \nu_\perp / \nu_\parallel$ given by equation (4) vanishes. This limit applies to low densities ($k_z \lambda_e > 1$) where the electron thermal conductivity is infinite, hence $C_\chi \rightarrow \infty$ in (2a). We have also found that it applies to high densities because of the energy transfer terms in (2ab) previously neglected. Hence, for $k_z \lambda_e \leq \sqrt{m/M}$, energy transfer terms dominate finite heat conduction terms in $\overline{\chi} / (\overline{\chi} - \overline{\xi})$, which approaches unity and the isothermal limit for $R_T \sim 1$. This eliminates the entropy instability even when parallel ion pressure is neglected. This result is valid for a low ratio of neutral to coulomb collision frequencies $\nu_{in}/\nu_{ii} > 2\sqrt{m/M}$ at $T_e = T_i = T_n$, where the ion energy loss rate to the neutrals exceeds the ion energy transfer rate back to the electrons[2].

In a fully ionized plasma there is a balance of energy exchange between ions and electrons, the asymptotic behavior at high densities is adiabatic rather than isothermal, and the entropy mode is not eliminated by energy transfer. However, the acoustic constraint which requires $k_z\lambda_e > \frac{1}{2}\sqrt{m/M}$ still applies.

While the acoustic constraint exactly stabilizes the entropy mode for $k_z\lambda_e < \frac{1}{2}\sqrt{m/M}$, the energy transfer terms have an assymptotic affect, and begin to dominate finite heat conduction terms for $k_z\lambda_e \leqslant \sqrt{m/M}$. Hence energy transfer to neutrals will restrict the entropy instability in a partially ionized plasma to even lower densities (N) than the fully ionized case.

Conclusion

We have found that retaining parallel ion pressure neglected by Tsai *et al.*[1] yields an acoustic correction to the entropy mode which stabilizes it at high densities $N = 0.3\, L_\perp / \lambda_e \geqslant 8.7$ in general. In a partially ionized plasma it may be stabilized at even lower densities by energy transfer to the neutrals which effectively makes the plasma isothermal for $\nu_{in}/\nu_{ii} > 2\sqrt{m/M}$ and $k_z\lambda_e \leqslant \sqrt{m/M}$. At these low densities the drift mode typically grows faster than the entropy mode for the same parameters, thereby surpressing the significance of the entropy mode as a linear instability.

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7. Hudson, M. K. and C. F. Kennel, submitted to J. Geophys. Res., (1974).

Figure Caption

Figure 1

Plot of maximum unstable density parameter $N = 0.3\, L_{\perp}/\lambda_e$ vs. $\nu_{\perp}/\nu_{\parallel}$ for a fully ionized plasma determined by the acoustic constraint $k_z \lambda_e \leqslant \frac{1}{2}\sqrt{m/M}$.

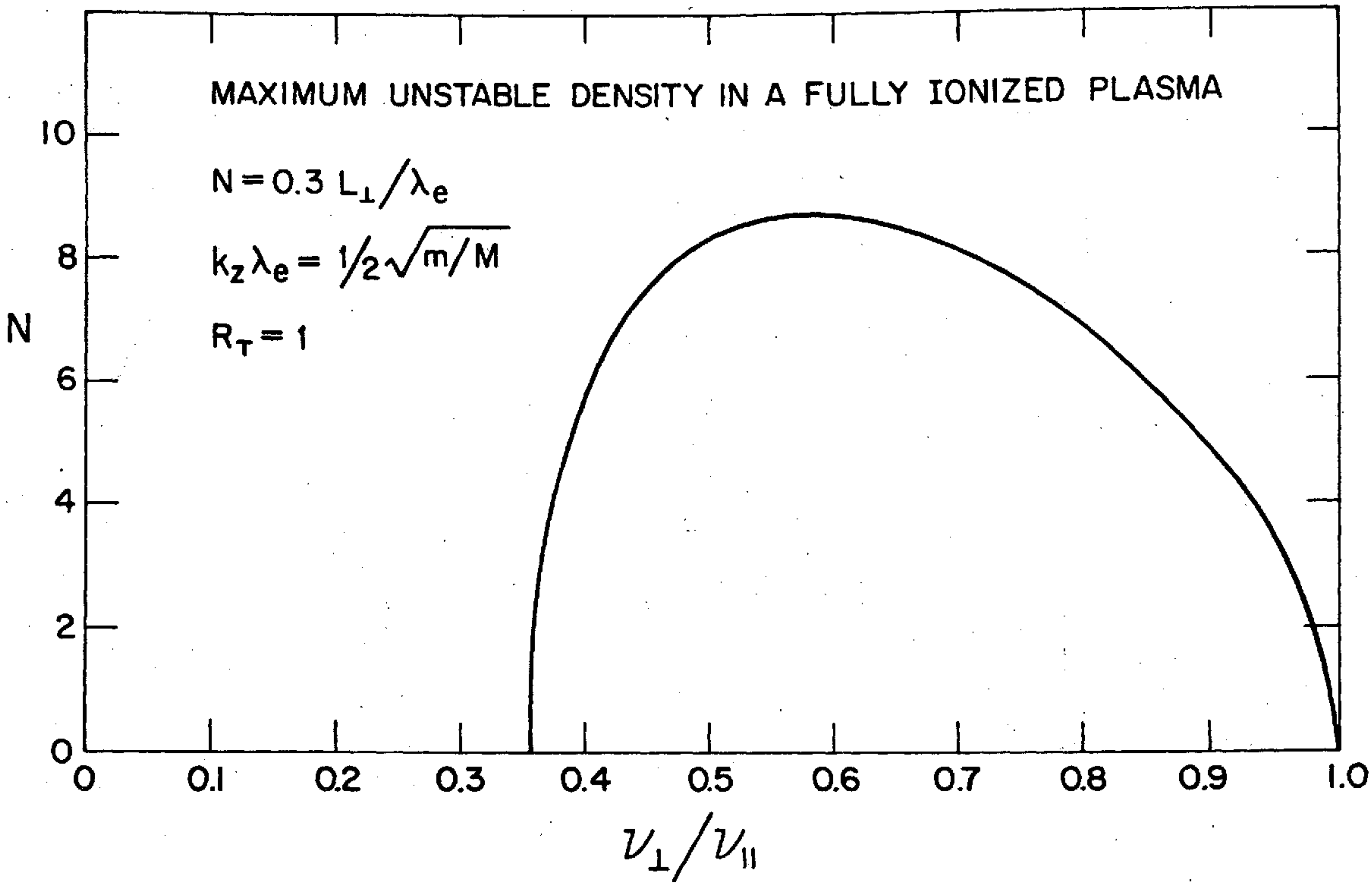
MAXIMUM UNSTABLE DENSITY IN A FULLY IONIZED PLASMA
$N = 0.3\, L_\perp / \lambda_e$
$k_z \lambda_e = 1/2 \sqrt{m/M}$
$R_T = 1$
N
0
2
4
6
8
10
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
$\nu_\perp / \nu_\parallel$

Figure 1

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